APPALACHIAN HIGHLANDS NETWORK

ASSESSING THE RISK OF FOLIAR INJURY FROM OZONE ON VEGETATION IN PARKS IN THE APPALACHIAN HIGHLANDS NETWORK

October 2004

Objective

This assessment employs a biologically-based method to evaluate the risk of foliar injury from ozone at parks within the 32 Vital Signs Networks. The assessment allows resource managers at each park to better understand the risk of ozone injury to vegetation within their park and permits them to make a better informed decision regarding the need to monitor the impacts of ozone on plants.

This introduction provides an overview of the risk assessment process and the data used. It also provides a summary of the results of risk assessments for sites within the network.

Risk Assessment Methodology

The risk assessment is based on a Triad model that holds that the response of a plant to ozone is the result of the interaction of the plant, the level of exposure and the exposure environment. While interactions among the three variables determine the response, the state of any one of them can serve to accentuate or preclude the production of foliar injury. The response is greatest when all three variables and their interactions are optimized relative to the conditions that foster injury. The optimized states are: the species of plants are highly sensitive to ozone, the exposure levels of ozone significantly exceed the thresholds for foliar injury, and the environmental conditions foster gas exchange and the uptake of ozone by plants.

To conduct a risk assessment for a specific site, information was obtained on the ozone-sensitive plant species found there, the levels of ozone exposure that occur over a number of years, and, since soil moisture is a critical variable controlling gas exchange, the levels of soil moisture that exist during the periods of ozone exposure. The information was evaluated to determine the degree to which the levels of ozone exposure and soil moisture conditions integrate to create an environment that leads to the production of foliar injury on sensitive species at the site.

Ozone-Sensitive Plant Species

In 2003 a workshop was convened by the National Park Service to review the ozone research literature and apply the field experience of the attendees to develop a comprehensive list of ozone-sensitive plant species for the eastern and western United States. Because of the emphasis of previous field studies and research, information on the ozone-sensitivity of tropical, arctic and rare species is limited. The workshop

identified both sensitive and bioindicator species for ozone, and published its determinations in a National Park Service Report (U.S. National Park Service 2003). An ozone bioindicator species is one whose high level of sensitivity and characteristic pattern of foliar injury allow it to be confidently used to ascertain the occurrence of injurious levels of ozone exposure in the field. With regard to the Triad model, a bioindicator species integrates the effects of exposure and environment while optimizing plant sensitivity. A bioindicator serves as an early-warning agent for the plant community with respect to the potential impacts of ozone. Ozone-sensitive and bioindicator plant species at each site were identified by comparing the site's floral list from NPSpecies with the list of sensitive species developed at the workshop.

Levels of Ozone Exposure

Ozone exposure data for 1995 through 1999 for each site were obtained either from on-site monitoring or by kriging. Both monitored and kriged data have limitations. Ozone monitoring was conducted at relatively few sites, but provides the most accurate assessment of ozone exposure. However, data from a single monitor may not accurately represent exposures throughout a large park, or a park with significant elevation differences. For sites without monitoring, ozone data were statistically estimated using a technique known as kriging. This technique uses ozone data from near-by monitoring sites to estimate data for the point of interest. Most of the sites in the risk assessment have kriged data. The accuracy of the kriged data depends on the number of near-by monitoring sites, their distance and their spatial arrangement. The accuracy with which the kriged data represents the actual exposure conditions is likely to vary among the sites.

All ozone data, both monitored and kriged, were analyzed by the Air Resources Division of the National Park Service to produce annual indices of exposure for 1995 through 1999 for each site. Since the ozone research community has not completely accepted one index of exposure as fully characterizing the threshold for foliar injury to vegetation, the assessment employed three indices to assure a comprehensive approach was taken in the assessment.

One index is the Sum06 and its attendant thresholds for injury (Heck and Cowling 1997). This index is comprised of the 90-day maximum sum of the 0800 through 1959 hourly concentrations of ozone $\geq$ 60 ppb (0.60 ppm). The index is calculated over running 90-day periods and the maximum sum can occur over any period of the year, although the chemistry of ozone generation usually results in it occurring over the summer months. For risk assessment purposes, it is also necessary to know the three-month period over which each year's maximum index occurs.

Another index is the W126 and its associated thresholds (Lefohn et al. 1997). The W126 index is the weighted sum of the 24 one-hour ozone concentrations daily from April through October, and the number of hours of exposure to concentrations $\geq$ 100 ppb (0.10 ppm) during that period. The W126 index uses a sigmoidal weighting function in producing the sum: the lower concentrations are given less weight than are the higher concentrations since the higher exposures play a greater role in producing injury. The

significance of the higher concentrations is also reflected in the requirement that there be a specified minimum number of hours of exposure to concentrations ≥ 100 ppb. Thus, the W126 index has two criteria that must be realized to satisfy its thresholds: a minimum sum of weighted concentrations and a minimum number of hours ≥ 100 ppb.

The last indicator of ozone exposure, designated N-value, consists of the numbers of hours of exposure each year that exceeded 60, 80 and 100 ppb. While there are no formal thresholds associated with these values, they provide insight to the distribution of exposures among these concentrations, and to the numbers of hours at and above 80 and 100 ppb, levels of exposure that are associated with the production of foliar injury.

Soil Moisture Status

Although gas exchange in plants is influenced by many environmental variables, soil moisture status is a critical factor since stomatal closure during periods of low soil moisture can severely limit gas exchange. Since site-specific soil moisture data are not available for the sites, the USDA's Palmer Z Index was selected to represent soil moisture conditions. The Palmer Z Index is a measure of the short-term departure of soil moisture from the long-term mean for the area. Consequently, the index automatically takes into account the diversity in precipitation among the parks, and emphasizes the difference that exists between the monthly soil moisture norm for the site and its actual state. The index is calculated monthly for up to ten regions in each of the 48 contiguous states, and measures drought on a scale from 0.0 to –4.0, a range representing normal to severe conditions. The regions are considered to be relatively homogeneous by USDA, but contain a diversity of soil, elevation and site variables that influence the soil moisture conditions at any specific location. The Palmer Z Index is not site specific and may not fully represent the soil moisture conditions at a park during a specific month.

The objective of this aspect of the risk assessment was to determine whether there is a consistent relationship between the level of ozone exposure and soil moisture status for the site by using the five years of data available. Atmospheric conditions that foster the production of ozone, such as clear sky, high UV levels and higher temperatures, are ones associated with the presence of few clouds and reduced precipitation. Consequently, years with high levels of atmospheric ozone may also experience low levels of soil moisture. This inverse relationship can constrain the uptake of ozone by plants in years with high levels of ozone and significantly reduce the likelihood that foliar injury will be produced. Knowing whether this relationship exists at a site is essential in determining whether certain levels of ozone exposure pose a risk to vegetation.

Palmer Z data were obtained from the USDA web site for 1995 through 1999 and tabulated for the three-month period over which the Sum06 exposure indices were compiled, and for the May to October period associated with the W126 exposure indices. Visual analysis of the exposure and soil moisture data was undertaken to determine whether there was an association between the two factors at each site.

Site-Specific Assessment

After information on the presence of sensitive species, levels of ozone exposure and relationships between exposure and soil moisture was compiled, it was synthesized into an assessment of risk of foliar injury for the site. Risk was classified as high, medium or low. Most sites had ozone-sensitive species on them and some of species were bioindicators that could be used in field surveys for ozone injury. If a site did not have any sensitive species, the risk assessment was completed and considered to be potential until sensitive species are identified.

The Sum06 and W126 exposure indices were examined to determine whether they exceeded their respective thresholds for injury, and the frequency with which the thresholds were exceeded over the five-year assessment period. The N-value data were examined to assess the distribution of exposures in a given year, and the consistency of exposure over the five years.

Evaluation of the relationship between ozone exposure and soil moisture might indicate they are inversely related, or they are not related and months of drought occur independent of the level of ozone exposure. At a site where exposure and drought are inversely related, the uptake of ozone is constrained by drought stress in the highest exposure years. In this instance, the risk of foliar ozone injury is likely greatest in years with lower levels of exposure that still exceed the injury thresholds and with soil moisture conditions that are more favorable for the uptake of ozone. In these cases, the greatest risk of foliar injury does not necessarily occur in the year with the highest level of ozone exposure. At sites where exposure and soil moisture are not related, the risk of foliar injury in a given year is a function of the random co-occurrence of high exposure and favorable moisture conditions.

The risk of foliar ozone injury at a site was determined by analyzing the plant, exposure and moisture data. The process was not quantitative, but based upon three primary evaluations: the extent and consistency by which the ozone injury thresholds were exceeded by the Sum06 and W126 exposure indices, the nature of the relationship between exposure and soil moisture, and the extent to which soil moisture conditions constrained the uptake of ozone in high exposure years. The evaluation of these factors and the assessment of their interactions with ozone-sensitive plant species is consistent with the Triad model of risk assessment, and comprises the framework for determining whether the risk of foliar ozone injury was high, moderate or low at each site. The accuracy of a site's risk assessment is dependent upon the quality of the plant list, the accuracy of the ozone exposure data and the degree to which the regional soil moisture data represent conditions at the site.

Sites receiving a risk rating of high have a probability of experiencing foliar injury in most years, while those rated low are not likely to experience injury in any year. A rating of moderate was assigned to sites where analysis indicated injury was likely to occur at some point in the five-year period, but the chance of injury occurring consistently was low. In other words, foliar injury will probably occur at sites rated moderate, but it is not

anticipated it will occur regularly or frequently. Sites rated moderate are likely to experience a wide temporal variation in the occurrence of injury, and over a period of time may experience injury for one or more years while also experiencing several years without injury.

Literature Cited

Heck, W.W. and E.B. Cowling. 1997. The Need for a Long-term Cumulative Secondary Ozone Standard - An Ecological Perspective. Environmental Management. January

Lefohn, AS, W Jackson, D. Shadwick, and HP Knudsen. 1997. Effect of surface ozone exposures on vegetation grown in the Southern Appalachian Mountains: identification of possible areas of concern. Atmospheric Environment 31(11):1695-1708.

U.S. National Park Service. 2003. Ozone Sensitive Plant Species on National Park Service and US Fish and Wildlife Service Lands. NPS D1522. Natural Resource Report NPS/NRARD/NRR-2003/01. Air Resources Division. Denver, CO. 21 pp. (Available at www2.nature.nps.gov/ard/pubs/index.htm)

SUMMARY OF RISK ASSESSMENTS FOR PARKS IN THE APPALACHIAN HIGHLANDS NETWORK

Park	Code	State	Risk	O3 Data
Big South Fork NRRA	BISO	TN	high	kriged
Blue Ridge PKWY	BLRI	NC	low	kriged
Great Smoky Mountains NP	GRSM	TN	high	monitored
Obed Wild and Scenic River	OBRI	TN	high	kriged

A portion of the Appalachian National Scenic Trail passes through the network. A stand-alone assessment of risk has been produced for sites along the Appalachian Trail.

BIG SOUTH FORK NATIONAL RIVER AND RECREATION AREA (BISO)

Plant Species Sensitive to Ozone

Latin Name	*Common Name*	*Family*
Ailanthus altissima	Tree-of-heaven	Simaroubaceae
Asclepias exaltata	Tall milkweed	Asclepiadaceae
Asclepias syriaca	Common milkweed	Asclepiadaceae
Aster macrophyllus	Big-leaf aster	Asteraceae
Aster umbellatus	Flat-toppped aster	Asteraceae
Cercis canadensis	Redbud	Fabaceae
Fraxinus americana	White ash	Oleaceae
Fraxinus pennsylvanica	Green ash	Oleaceae
Liquidambar styraciflua	Sweetgum	Hamamelidaceae
Liriodendron tulipifera	Yellow-poplar	Magnoliaceae
Parthenocissus quinquefolia	Virginia creeper	Vitaceae
Pinus rigida	Pitch pine	Pinaceae
Pinus taeda	Loblolly pine	Pinaceae
Pinus virginiana	Virginia pine	Pinaceae
Platanus occidentalis	American sycamore	Platanaceae
Prunus serotina	Black cherry	Rosaceae
Rhus copallina	Flameleaf sumac	Anacardiaceae
Robinia pseudoacacia	Black locust	Fabaceae
Rubus allegheniensis	Allegheny blackberry	Rosaceae
Rudbeckia laciniata	Cut-leaf coneflower	Asteraceae
Sambucus canadensis	American elder	Caprifoliaceae
Sassafras albidum	Sassafras	Lauraceae
Verbesina occidentalis	Crownbeard	Asteraceae
Vitis labrusca	Northern fox grape	Vitaceae

Representative Ozone Injury Thresholds

Sum06 -- The running 90-day maximum sum of the 0800-2000 hourly ozone concentrations of ozone equal to or greater than 0.06 ppm. Index is in cumulative ppm-hr.

Natural Ecosystems	8 - 12 ppm-hr	(foliar injury)
Tree Seedlings	10 - 16 ppm-hr	(1-2% reduction in growth)
Crops	15 - 20 ppm-hr	(10% reduction in 25-35% of crops)

W126 -- A cumulative index of exposure that uses a sigmoidal weighting function to give added significance to higher concentrations of ozone while retaining and giving less weight to mid and lower concentrations. The number of hours over 100 ppb (N100) is also considered in assessing the possible impact of the exposure. The W126 index is in cumulative ppm-hr.

	W126	N100
Highly Sensitive Species	5.9 ppm-hr	6
Moderately Sensitive Species	23.8 ppm-hr	51
Low Sensitivity	66.6 ppm-hr	135

Ozone Exposure Data

Ambient concentrations of ozone were not monitored on-site, but were estimated by kriging, a statistical interpolation process. The estimated hourly concentrations of ozone were then used to generate annual exposure values for the site. The exposure values include the Sum06 and W126 exposure indices in ppm-hr and the annual number of hours above 60, 80 and 100 ppb (N60, N80 and N100, respectively).

Ozone air quality data for BISO					
	1995	1996	1997	1998	1999
Sum06	26	21	26	37	41
W126	38.4	34.1	39.2	56.6	61.3
N60	695	616	709	1004	1112
N80	120	101	116	226	249
N100	17	8	10	34	24

Soil Moisture Status

The uptake of ambient ozone by a plant is highly dependent upon the environmental conditions under which the exposure takes place. The level of soil moisture is an important environmental variable controlling the uptake of ozone. Understanding the soil moisture status can provide insight to how effective the exposure may have been in leading to foliar injury. The Palmer Z Index was used to indicate soil moisture status since it represents the short-term departure of soil moisture from the average for that time period for the site. The objectives of the assessment were to examine the relationship between high annual levels of ozone and soil moisture status, and to consider the impact reduced soil moisture status would have on the effectiveness of exposure.

Palmer Z data were compiled for the site for both the months used to calculate the Sum06 index and for the April through October period for the W126 index for 1995 through 1999. The index ranges from approximately +4.0 (extreme wetness) to –4.0 (extreme drought) with ±0.9 representing normal soil moisture.

Soil moisture status for the Sum06 index period.

Palmer Z Index data for 3-month Sum06 period at BISO					
	1995	1996	1997	1998	1999
Month 1	1.05	-0.16	-3.06	0.23	3.52
Month 2	-1.28	0.98	-0.75	0.33	0.07
Month 3	-0.50	0.82	0.66	-2.51	-1.87

Soil moisture status for the April through October period for the W126 index.

Palmer Z Index data for the 7-month W126 period at BISO					
	1995	1996	1997	1998	1999
April	-1.05	0.28	0.06	4.35	-1.14
May	2.31	0.46	2.10	-0.31	0.18
June	1.05	-0.16	5.90	6.93	3.52
July	-1.28	0.98	-3.06	0.23	0.07
August	-0.50	0.82	-0.75	0.33	-1.87
September	0.81	2.45	0.66	-2.51	-2.48
October	3.77	-0.93	0.25	-1.30	-1.25

Risk Analysis

- There are numerous ozone-sensitive species at the site, some of which are bioindicators for ozone.

- The Sum06 index exceeds the threshold for injury to vegetation. The W126 accumulative value and the N100 count are greater than their threshold values, thus the criteria for injury under the W126 index are satisfied.

- The N-values for concentrations of 60, 80, and 100 ppb are all elevated and show there are a significant number of hours during which plants are exposed to levels of ozone likely to produce foliar injury.

- Soil moisture levels during the 90-day Sum06 accumulation periods were generally normal and favored the uptake of ozone. In the five-year assessment period there was one month of mild to severe drought in each of four years, with normal soil moisture in the fifth year. There is no apparent relationship between the Sum06 exposure index and soil moisture conditions. Soil moisture levels associated with the seasonal W126 index appear inversely related to ozone concentrations: when ozone is high, soil moisture is low. This relationship reduces the uptake of ozone and the effectiveness of the exposure in producing foliar injury. In the highest ozone years, 1999 and 1998, there were four and two months, respectively, of mild and moderate drought. The two mid-ozone years,

1995 and 1997, had two months of mild and one month of severe drought, respectively. In the lowest ozone year, 1996, soil moisture conditions were normal.

The risk of foliar ozone injury at Big South Fork National River and Recreation Area is high. While the levels of ozone exposure create the potential for injury each year, the inverse relationship between exposure and soil moisture reduces the likelihood of injury developing in the highest ozone years. The probability of foliar injury developing may be greatest during years such as 1996 when ozone levels are somewhat reduced but still exceed the thresholds and soil moisture is normal, and in 1998 when exposures are high and drought occurs late in the growing season.

A program to assess the incidence of foliar ozone injury on plants at the site could use one or more of the following bioindicator species: tree-of-heaven, tall milkweed, common milkweed, big-leaf aster, redbud, white ash, yellow-poplar, American sycamore, black cherry, cut-leaf coneflower, American elder, crownbeard and northern fox grape.

BLUE RIDGE PARKWAY (BLRI)

Plant Species Sensitive to Ozone

Latin Name	*Common Name*	*Family*
Ailanthus altissima	Tree-of-heaven	Simaroubaceae
Apocynum androsaemifolium	Spreading dogbane	Apocynaceae
Asclepias exaltata	Tall milkweed	Asclepiadaceae
Asclepias syriaca	Common milkweed	Asclepiadaceae
Aster acuminatus	Whorled aster	Asteraceae
Aster macrophyllus	Big-leaf aster	Asteraceae
Aster umbellatus	Flat-toppped aster	Asteraceae
Cercis canadensis	Redbud	Fabaceae
Fraxinus americana	White ash	Oleaceae
Fraxinus pennsylvanica	Green ash	Oleaceae
Krigia montana	Mountain dandelion	Asteraceae
Liquidambar styraciflua	Sweetgum	Hamamelidaceae
Liriodendron tulipifera	Yellow-poplar	Magnoliaceae
Parthenocissus quinquefolia	Virginia creeper	Vitaceae
Pinus banksiana	Jack pine	Pinaceae
Pinus rigida	Pitch pine	Pinaceae
Pinus virginiana	Virginia pine	Pinaceae
Platanus occidentalis	American sycamore	Platanaceae
Populus tremuloides	Quaking aspen	Salicaceae
Prunus serotina	Black cherry	Rosaceae
Rhus copallina	Flameleaf sumac	Anacardiaceae
Robinia pseudoacacia	Black locust	Fabaceae
Rubus allegheniensis	Allegheny blackberry	Rosaceae
Symphoricarpos albus	Common snowberry	Caprifoliaceae
Verbesina occidentalis	Crownbeard	Asteraceae

Representative Ozone Injury Thresholds

Sum06 -- The running 90-day maximum sum of the 0800-2000 hourly ozone concentrations of ozone equal to or greater than 0.06 ppm. Index is in cumulative ppm-hr.

Natural Ecosystems	8 - 12 ppm-hr	(foliar injury)
Tree Seedlings	10 - 16 ppm-hr	(1-2% reduction in growth)
Crops	15 - 20 ppm-hr	(10% reduction in 25-35% of crops)

W126 -- A cumulative index of exposure that uses a sigmoidal weighting function to give added significance to higher concentrations of ozone while retaining and giving less weight to mid and lower concentrations. The number of hours over 100 ppb (N100) is also considered in assessing the possible impact of the exposure. The W126 index is in

cumulative ppm-hr.

	W126	N100
Highly Sensitive Species	5.9 ppm-hr	6
Moderately Sensitive Species	23.8 ppm-hr	51
Low Sensitivity	66.6 ppm-hr	135

Ozone Exposure Data

Ambient concentrations of ozone were not monitored on-site, but were estimated by kriging, a statistical interpolation process. The estimated hourly concentrations of ozone were then used to generate annual exposure values for the site. The exposure values include the Sum06 and W126 exposure indices in ppm-hr and the annual number of hours above 60, 80 and 100 ppb (N60, N80 and N100, respectively).

Ozone air quality data for BLRI					
	1995	1996	1997	1998	1999
Sum06	7	18	12	20	19
W126	22.6	33.7	23.9	38.9	33.9
N60	235	544	340	736	576
N80	8	20	5	21	16
N100	0	0	0	3	0

Soil Moisture Status

The uptake of ambient ozone by a plant is highly dependent upon the environmental conditions under which the exposure takes place. The level of soil moisture is an important environmental variable controlling the uptake of ozone. Understanding the soil moisture status can provide insight to how effective the exposure may have been in leading to foliar injury. The Palmer Z Index was used to indicate soil moisture status since it represents the short-term departure of soil moisture from the average for that time period for the site. The objectives of the assessment were to examine the relationship between high annual levels of ozone and soil moisture status, and to consider the impact reduced soil moisture status would have on the effectiveness of exposure.

Palmer Z data were compiled for the site for both the months used to calculate the Sum06 index and for the April through October period for the W126 index for 1995 through 1999. The index ranges from approximately +4.0 (extreme wetness) to –4.0 (extreme drought) with ±0.9 representing normal soil moisture.

Soil moisture status for the Sum06 index period.

Palmer Z Index data for 3-month Sum06 period at BLRI					
	1995	1996	1997	1998	1999
Month 1	-0.22	-0.70	2.84	-2.57	1.24
Month 2	3.12	0.26	-1.17	-2.52	-0.91
Month 3	-1.62	-0.32	-3.35	-3.01	-2.64

Soil moisture status for the April through October period for the W126 index.

Palmer Z Index data for the 7-month W126 period at BLRI					
	1995	1996	1997	1998	1999
April	-2.81	0.22	2.05	3.84	-0.96
May	-0.22	-0.70	-0.13	-1.65	-0.39
June	3.12	0.26	2.84	0.73	1.24
July	-1.62	-0.32	-1.17	-2.57	-0.91
August	1.98	1.36	-3.35	-2.52	-2.64
September	-0.16	2.86	1.59	-3.01	-1.75
October	3.09	-1.80	0.65	-1.32	-0.37

Risk Analysis

- There are numerous ozone-sensitive species at the site, some of which are bioindicators for ozone.

- The Sum06 index generally exceeds the threshold for injury to vegetation. While the W126 accumulative value exceeds the threshold, the N100 count shows that the one-hour concentration of ozone reached 100 ppb in only one year, and thus the criteria for injury under the W126 exposure index are not satisfied.

- The N-values for the site show only a few hours in which concentrations exceeded 80 ppb, and only one year in which the concentration reached 100 ppb. These levels of exposure are not likely to injure vegetation.

- Although the year with the highest Sum06 and W126 index of exposure, 1998, also had the most months of drought stress, there is no overall association between ozone and drought for either index of exposure. The three highest Sum06 indices in 1998, 1999 and 1996 were similar in magnitude, but accompanied by three months of moderate and severe drought, one month of moderate drought, and normal moisture conditions, respectively. The highest W126 index occurred in 1998 and was associated with five months of mild to severe drought. The two mid-exposure years, 1996 and 1999, experienced one and two months of mild and moderate drought, respectively. There were two

months of mild to severe drought in each of the two lowest exposure years, 1997 and 1995. Overall, there is no apparent association between the W126 index of exposure and drought stress.

The low levels of ozone exposure at Blue Ridge Parkway make the risk of foliar ozone injury to plants low. The Sum06 exposure threshold is generally satisfied, but the W126 criteria are not. While there are some hours with concentrations of ozone above 80 ppb, the numbers are not high and concentrations of 100 ppb are rare. Soil moisture conditions and ozone exposure levels are not related, and conditions constraining uptake can occur at any level of ozone exposure.

If a program to assess the incidence of foliar ozone injury on plants at the site is initiated at some point in the future, one or more of the following bioindicator species could be used: tree-of-heaven, spreading dogbane, tall milkweed, common milkweed, big-leaf aster, redbud, white ash, yellow-poplar, American sycamore, quaking aspen, black cherry, common snowberry and crownbeard.

GREAT SMOKY MOUNTAINS NATIONAL PARK (GRSM)

Plant Species Sensitive to Ozone

Latin Name	*Common Name*	*Family*
Ailanthus altissima	Tree-of-heaven	Simaroubaceae
Apocynum androsaemifolium	Spreading dogbane	Apocynaceae
Asclepias exaltata	Tall milkweed	Asclepiadaceae
Asclepias syriaca	Common milkweed	Asclepiadaceae
Aster acuminatus	Whorled aster	Asteraceae
Aster macrophyllus	Big-leaf aster	Asteraceae
Aster umbellatus	Flat-toppped aster	Asteraceae
Cercis canadensis	Redbud	Fabaceae
Fraxinus americana	White ash	Oleaceae
Fraxinus pennsylvanica	Green ash	Oleaceae
Krigia montana	Mountain dandelion	Asteraceae
Liquidambar styraciflua	Sweetgum	Hamamelidaceae
Liriodendron tulipifera	Yellow-poplar	Magnoliaceae
Parthenocissus quinquefolia	Virginia creeper	Vitaceae
Pinus rigida	Pitch pine	Pinaceae
Pinus taeda	Loblolly pine	Pinaceae
Pinus virginiana	Virginia pine	Pinaceae
Platanus occidentalis	American sycamore	Platanaceae
Prunus serotina	Black cherry	Rosaceae
Robinia pseudoacacia	Black locust	Fabaceae
Rubus allegheniensis	Allegheny blackberry	Rosaceae
Rudbeckia laciniata	Cut-leaf coneflower	Asteraceae
Sambucus canadensis	American elder	Caprifoliaceae
Verbesina occidentalis	Crownbeard	Asteraceae

Representative Ozone Injury Thresholds

Sum06 -- The running 90-day maximum sum of the 0800-2000 hourly ozone concentrations of ozone equal to or greater than 0.06 ppm. The index is in cumulative ppm-hr.

Natural Ecosystems	8 - 12 ppm-hr	(foliar injury)
Tree Seedlings	10 - 16 ppm-hr	(1-2% reduction in growth)
Crops	15 - 20 ppm-hr	(10% reduction in 25-35% of crops)

W126 -- A cumulative index of exposure that uses a sigmoidal weighting function to give added significance to higher concentrations of ozone while retaining and giving less weight to mid and lower concentrations. The number of hours over 100 ppb (N100) is also considered in assessing the possible impact of the exposure. The W126 index is in

cumulative ppm-hr.

	W126	N100
Highly Sensitive Species	5.9 ppm-hr	6
Moderately Sensitive Species	23.8 ppm-hr	51
Low Sensitivity	66.6 ppm-hr	135

Ozone Exposure Data

Ambient concentrations of ozone monitored on-site were analyzed to generate annual exposure values. The values include the Sum06 and W126 exposure indices in ppm-hr and the annual number of hours above 60, 80 and 100 ppb (N60, N80 and N100, respectively).

Lookout Rock

Ozone air quality data for GRSM – Lookout Rock					
	1995	1996	1997	1998	1999
Sum06	33	35	47	46	54
W126	66.9	76.6	92.8	120.6	128.8
N60	1270	1490	1686	2102	2240
N80	218	175	374	558	617
N100	24	5	42	105	82

Cade's Cove

Ozone air quality data for GRSM – Cade's Cove					
	1995	1996	1997	1998	1999
Sum06	16	18	22	27	36
W126	23.6	24.3	30.6	42.2	47.4
N60	410	452	570	742	877
N80	33	21	56	131	159
N100	4	0	1	5	8

Cove Mountain

Ozone air quality data for GRSM – Cove Mountain					
	1995	1996	1997	1998	1999
Sum06	36	38	44	55	57
W126	95.7	98.7	106.2	142.6	141.3
N60	1856	1990	2019	2566	2511
N80	247	248	368	680	680
N100	18	8	15	107	54

Clingman's Dome

Ozone air quality data for GRSM – Clingman's Dome					
	1995	1996	1997	1998	1999
Sum06	18	31	35	51	51
W126	65.9	74.2	90.0	136.2	133.9
N60	1300	1489	1786	2577	2568
N80	127	124	188	617	510
N100	5	3	5	57	29

Soil Moisture Status

The uptake of ambient ozone by a plant is highly dependent upon the environmental conditions under which the exposure takes place, and the level of soil moisture is an important environmental variable controlling the process. Understanding the soil moisture status can provide insight to how effective an exposure may be in leading to foliar injury. The Palmer Z Index was selected to indicate soil moisture status since it represents the short-term departure of soil moisture from the average for each month for the site. The objectives of the assessment were to examine the relationship between high annual levels of ozone and soil moisture status, and to consider the impact reduced soil moisture status would have on the effectiveness of exposure.

The Palmer Z Index is calculated for up to 10 regions within a state and therefore is not a site-specific index. Without site-specific data, ozone/soil moisture relationships can only be estimated. Site-specific criteria such as aspect, elevation, and soil type can alter soil moisture conditions such that they depart from those determined for the region. However, in lieu of site-specific data, the Palmer Z Index is the best estimate of short-term soil moisture status and its change throughout the growing season.

Palmer Z data were compiled for the site for both the months used to calculate the Sum06 index and for the April through October period for the W126 index for 1995 through 1999. The Palmer Z index ranges from approximately +4.0 (extreme wetness) to –4.0 (extreme drought) with ±0.9 representing normal soil moisture.

Soil moisture status for the Sum06 index period.

Palmer Z Index data for 3-month Sum06 period at GRSM					
	1995	1996	1997	1998	1999
Month 1	1.37	-0.09	-0.80	-0.89	1.52
Month 2	-2.96	1.38	-1.53	-1.71	-2.38
Month 3	-1.51	1.32	1.39	-2.87	-1.82

Soil moisture status for the April through October period for the W126 index.

Palmer Z Index data for the 7-month W126 period at GRSM					
	1995	1996	1997	1998	1999
April	-2.42	0.78	1.59	7.53	-0.78
May	2.15	1.14	2.08	-0.33	0.42
June	1.37	-0.09	3.01	3.96	2.45
July	-2.96	1.38	-0.80	-0.89	1.52
August	-1.51	1.32	-1.53	-1.71	-2.38
September	0.24	2.32	1.39	-2.87	-1.82
October	1.38	-0.86	0.51	-2.35	-0.58

Risk Analysis

- There are numerous ozone-sensitive species at the site, some of which are bioindicators for ozone.

- The Sum06 index significantly exceeds the threshold for foliar injury at each of the sites. The W126 accumulative value significantly exceeds the threshold at each site, however the N100 count is highly variable both among sites and years. The number of hours above 100ppb ozone often, but not consistently, meets the threshold for injury under the W126 criterion for injury to vegetation.

- The N-values for concentrations of 60 and 80 ppb are very high and demonstrate that there are a significant numbers of hours during which plants are exposed to potentially harmful levels of ozone. While the N100 index is highly variable, site-years with 10 hours of concentrations greater than 100 ppb are common and there are five site-years with over 50 hours of ozone greater than 100 ppb.

- Relationships between levels of ozone exposure and soil moisture were assessed using data for Lookout Rock and Cove Mountain sites since they generally had the highest levels of exposure. There does not appear to be any association between the 90-day Sum06 accumulative index and soil moisture conditions. The highest exposure years, 1998 and 1999, and the lowest year, 1995, each experienced two months of mild and moderate drought. Soil moisture levels

associated with the seasonal W126 index appear inversely related to ozone concentrations: when ozone is high, soil moisture is low, although the pattern is not consistent. This relationship reduces the uptake of ozone and the effectiveness of the exposure in producing foliar injury. In the highest ozone years, 1998 and 1999, there were three and two months, respectively, of mild and moderate drought. The two mid-ozone years, 1997 and 1996, had one month of mild drought and normal moisture conditions. In the lowest ozone year, 1995, there were three months of mild and moderate drought.

The risk of foliar ozone injury to plants at Great Smoky Mountains National Park is high. The threshold for the Sum06 index is consistently exceeded at all sites, while the threshold for the W126 index is consistently exceeded at some sites and occasionally at others. Hours of exposure at 80 and 100 ppb vary widely among sites and years. Although the levels of ozone exposure create the potential for injury, dry soil conditions may reduce the likelihood of injury developing in high exposure years. Since the park is subject to potentially harmful levels of ozone annually, the probability of foliar injury developing may be greatest during years such as 1997 and 1999 when ozone levels are somewhat reduced but still exceed the thresholds, and soil moisture levels are normal or under mild drought and do not significantly constrain the uptake of ozone. While all four Smoky Mountain sites have a high risk for ozone injury, the Cade's Cove site shows levels of ozone distinctly lower than those at the other three sites. Exposure trends among the four sites are similar with the highest exposures occurring in the same years at all sites and the lowest exposures in the same years. Thus it is likely that the level of risk of ozone injury will be similar among all four sites in any given year.

A program to assess the incidence of foliar ozone injury on plants at the site could use one or more of the following bioindicator species: tree-of-heaven, spreading dogbane, tall milkweed, common milkweed, big-leaf aster, redbud, white ash, yellow-poplar, American sycamore, black cherry, cut-leaf coneflower, American elder and crownbeard.

OBED WILD AND SCENIC RIVER (OBRI)

Plant Species Sensitive to Ozone

Latin Name	*Common Name*	*Family*
Ailanthus altissima	Tree-of-heaven	Simaroubaceae
Asclepias exaltata	Tall milkweed	Asclepiadaceae
Asclepias syriaca	Common milkweed	Asclepiadaceae
Aster umbellatus	Flat-toppped aster	Asteraceae
Cercis canadensis	Redbud	Fabaceae
Fraxinus americana	White ash	Oleaceae
Fraxinus pennsylvanica	Green ash	Oleaceae
Liquidambar styraciflua	Sweetgum	Hamamelidaceae
Liriodendron tulipifera	Yellow-poplar	Magnoliaceae
Parthenocissus quinquefolia	Virginia creeper	Vitaceae
Pinus taeda	Loblolly pine	Pinaceae
Pinus virginiana	Virginia pine	Pinaceae
Platanus occidentalis	American sycamore	Platanaceae
Prunus serotina	Black cherry	Rosaceae
Robinia pseudoacacia	Black locust	Fabaceae
Rubus allegheniensis	Allegheny blackberry	Rosaceae
Rudbeckia laciniata	Cut-leaf coneflower	Asteraceae
Sambucus canadensis	American elder	Caprifoliaceae
Sassafras albidum	Sassafras	Lauraceae
Verbesina occidentalis	Crownbeard	Asteraceae
Vitis labrusca	Northern fox grape	Vitaceae

Representative Ozone Injury Thresholds

Sum06 -- The running 90-day maximum sum of the 0800-2000 hourly ozone concentrations of ozone equal to or greater than 0.06 ppm. Index is in cumulative ppm-hr.

Natural Ecosystems	8 - 12 ppm-hr	(foliar injury)
Tree Seedlings	10 - 16 ppm-hr	(1-2% reduction in growth)
Crops	15 - 20 ppm-hr	(10% reduction in 25-35% of crops)

W126 -- A cumulative index of exposure that uses a sigmoidal weighting function to give added significance to higher concentrations of ozone while retaining and giving less weight to mid and lower concentrations. The number of hours over 100 ppb (N100) is also considered in assessing the possible impact of the exposure. The W126 index is in cumulative ppm-hr.

	W126	N100
Highly Sensitive Species	5.9 ppm-hr	6
Moderately Sensitive Species	23.8 ppm-hr	51
Low Sensitivity	66.6 ppm-hr	135

Ozone Exposure Data

Ambient concentrations of ozone were not monitored on-site, but were estimated by kriging, a statistical interpolation process. The estimated hourly concentrations of ozone were then used to generate annual exposure values for the site. The exposure values include the Sum06 and W126 exposure indices in ppm-hr and the annual number of hours above 60, 80 and 100 ppb (N60, N80 and N100, respectively).

Ozone air quality data for OBRI					
	1995	1996	1997	1998	1999
Sum06	17	17	15	18	24
W126	40.9	41.1	47.0	63.6	63.6
N60	727	750	845	1118	1147
N80	140	129	154	270	267
N100	22	11	13	42	31

Soil Moisture Status

The uptake of ambient ozone by a plant is highly dependent upon the environmental conditions under which the exposure takes place. The level of soil moisture is an important environmental variable controlling the uptake of ozone. Understanding the soil moisture status can provide insight to how effective the exposure may have been in leading to foliar injury. The Palmer Z Index was used to indicate soil moisture status since it represents the short-term departure of soil moisture from the average for that time period for the site. The objectives of the assessment were to examine the relationship between high annual levels of ozone and soil moisture status, and to consider the impact reduced soil moisture status would have on the effectiveness of exposure.

Palmer Z data were compiled for the site for both the months used to calculate the Sum06 index and for the April through October period for the W126 index for 1995 through 1999. The index ranges from approximately +4.0 (extreme wetness) to –4.0 (extreme drought) with ±0.9 representing normal soil moisture.

Soil moisture status for the Sum06 index period.

Palmer Z Index data for 3-month Sum06 period at OBRI					
	1995	1996	1997	1998	1999
Month 1	1.05	-0.16	-3.06	6.93	0.07
Month 2	-1.28	0.98	-0.75	0.23	-1.87
Month 3	-0.50	0.82	0.66	0.33	-2.48

Soil moisture status for the April through October period for the W126 index.

Palmer Z Index data for the 7-month W126 period at OBRI					
	1995	1996	1997	1998	1999
April	-1.05	0.28	0.06	4.35	-1.14
May	2.31	0.46	2.10	-0.31	0.18
June	1.05	-0.16	5.90	6.93	3.52
July	-1.28	0.98	-3.06	0.23	0.07
August	-0.50	0.82	-0.75	0.33	-1.87
September	0.81	2.45	0.66	-2.51	-2.48
October	3.77	-0.93	0.25	-1.30	-1.25

Risk Analysis

- There are numerous ozone-sensitive species at the site, some of which are bioindicators for ozone.

- The Sum06 index exceeds the threshold for injury to vegetation. The W126 accumulative value and the N100 count are greater than their threshold values, thus the criteria for injury under the W126 index are satisfied. The Sum06 and W126 indices both exceed the levels considered necessary for injury to vegetation.

- The N-values for concentrations of 60, 80, and 100 ppb are all elevated and show there are a significant numbers of hours during which plants are exposed to levels of ozone likely to produce foliar injury.

- There is no relationship between the 90-day Sum06 accumulation period index of ozone and soil. The highest exposure year, 1999, had two months of mild and moderate drought, while the lowest year, 1997, had one month of severe drought. There was one month of mild drought in the remaining three mid-exposure years. Soil moisture levels associated with the seasonal W126 index appear inversely related to ozone concentrations: when ozone is high, soil moisture is low, although the pattern is inconsistent. This relationship reduces the uptake of ozone and the effectiveness of the exposure in producing foliar injury. The highest

ozone years, 1998 and 1999, experienced two and four months of mild to moderate drought. The mid-exposure year 1997 had one month of severe drought. Soil moisture in the two lowest years, 1995 and 1996, consisted of two months of mild drought and normal moisture conditions, respectively.

The risk of foliar ozone injury to plants at Obed Wild and Scenic River is high. The levels of ozone exposure consistently create the potential for injury, however dry soil conditions may reduce the likelihood of injury, particularly in a high exposure year. Levels of exposure capable of producing foliar injury also occur under conditions of minor drought and normal soil moisture. The probability of foliar injury developing may be greatest during years such as 1995 and 1996 when ozone levels are somewhat reduced but still exceed the thresholds, and soil moisture levels are normal or under mild drought and do not significantly constrain the uptake of ozone.

A program to assess the incidence of foliar ozone injury on plants at the site could use one or more of the following bioindicator species: tree-of-heaven, tall milkweed, common milkweed, redbud, white ash, yellow-poplar, American sycamore, black cherry, cut-leaf coneflower, American elder, crownbeard and northern fox grape.